# USE OF THERMAL INFRARED AND COLOUR INFRARED IMAGERY TO DETECT CROP MOISTURE STRESS

INTERIM REPORT

March, 1979

R.C. McKenzie[1], N.F. Clark[2], and J. Cihlar[3]

Sponsored By:

ALBERTA REMOTE SENSING CENTER

CANADA CENTRE FOR REMOTE SENSING

ALBERTA AGRICULTURE



[1] Soil and Water Specialist, Alberta Agriculture, Irrigation Division, Brooks.

[2] Irrigation Technologist, Alberta Agriculture, Irrigation Division, Brooks.

[3] Environmental Scientist, Canada Centre for Remote Sensing, Ottawa.

TABLE OF CONTENTS

## LIST OF FIGURES

## LIST OF TABLES

## 1. INTRODUCTION

In southern Alberta, intensive agriculture is possible only on irrigated land. Irrigated crops must be provided with adequate amounts of water, but the periodic water shortages (such as in 1977 due to less-than-normal rainfall) and the expanding total area of irrigated land demand that water use be made more efficient. Thus, the 1978 Oldman River Report recommended that irrigation scheduling programs be enlarged and improved to increase water use efficiency. However, previous irrigation scheduling services have encountered difficulties because of the inability to adequately monitor moisture status of crops. Since crop water requirements may differ from one field to another as well as within fields, a complete soil moisture sampling program would be very expensive.

Preliminary studies conducted in the U.S. (e.g. Millard et al., 1977) have shown that crop moisture stress may be detected by using aircraft remote sensing data. The purpose of the project described here was to evaluate whether remote sensing data can provide information that would be useful to supplement ground observation in an irrigation scheduling program.

## 2. DATA ACQUISITION

Fifteen farm fields with different crops (irrigated corn, alfalfa, fall rye, potatoes, flax, and peas; unirrigated wheat, summerfallow, and native range) were chosen for the study. Five small experimental plots, each containing three water treatments and four replicates, were also included. They contained potatoes and carrots (at Cassils), cabbage and mustard (Duchess), and faba beans (Rockyford).

Two missions were undertaken by Canada Centre for Remote Sensing (CCRS) on June 21 and August 5, 1978. Each mission consisted of a day flight during which colour infrared and thermal infrared imagery were simultaneously obtained, and a night flight with only thermal imagery being collected. CCRS acquired photographs at 1:4,100 for the irrigation plots and 1:50,000 for all sites.

Two additional flights were made on July 24 and August 18 by Kenting Air Services on a contract from the Alberta Remote Sensing Centre. They obtained day colour infrared photographs on a 1:2,500 scale from the irrigation plots and 1:10,000 scale for all sites.

At the time of each flight, the irrigation plots were sampled to determine soil moisture gravimetrically. Twelve sites on each irrigation plot were sampled, one for each of the 3 water treatments and four replicates. Samples from

four depths (30cm increments) were taken at each sample site. At the time of each CCRS flight, twelve to fifteen fields were sampled, while seven fields were sampled at the time of each Kenting flight. Six sites were sampled in each farm field and four depths (30cm increments) were taken per sample site. The above sampling procedure thus produced approximately 1,800 soil moisture samples during the experiment.

Soil texture was determined for each site, and both field capacity (FC) and permanent wilting point (PWP) were derived from the soil texture and available data (both published and unpublished). Using the above parameters and root depths obtained from the Alberta Agriculture irrigation scheduling program, the amount of available water (AW, in percent) was determined for each irrigation plot and each of the six sites within the farm fields as follows:

$$AW = \frac{WC - PWP}{FC - PWP} \times 100, \quad (\%)$$

where WC is the total water content in cm and all three variables refer to the root zone.

In addition to soil moisture samples, ground colour infrared photographs and normal colour photographs of the irrigation plots and farm fields were taken at the time of each flight. Measurements of crop canopy temperatures were also made with a portable radiation thermometer PRT-5 a number of times during the summer.

## 3. DATA ANALYSIS

Colour infrared aerial photographs processed as positive transparencies and thermal images in both analogue and level-sliced form were used for the analysis. Densitometric measurements of each sampled field site (on the small scale photography) and irrigation plot (large scale photography) were made using a Macbeth transmission densitometer TD-504, separately for each emulsion layer.

Thermogram analysis was carried out in three steps. First, analogue low altitude thermograms were displayed on a density slicer and the individual treatment/replicate combinations were ranked from coldest (=1) to warmest (=12), separately for day and night data. An average rank value was then computed for each treatment/plot (crop) /time (day or night) combination. Secondly, the apparent temperature "slice" was determined for each sampled site on the low altitude (irrigated plots) and high altitude (farm fields) level-sliced

thermograms. This procedure was considered necessary because the level sliced thermograms contained relatively coarse temperature slices, particularly for the daytime images. As the third step, regression analysis was carried out using the farm fields data. For this analysis, average values were computed for all sites within one field which were located in the same temperature "slice"; emulsion densities and AW values were included in this averaging process. Results presented in the following section refer to data obtained on August 5, 1978. These data were given higher priority because moisture stress was more evident at that time.

## 4. RESULTS AND DISCUSSION

Figure 1 shows the plot of apparent temperature rank as a function of available water. Each point is an average of four rank values (4 replicates/treatment). The apparent temperature increased with decreasing available water in the range of 110 to 40%. The relative response to changing moisture availability was similar for all crops studied and for both day and night measurements, although its uniformity was lower for cabbage and mustard (Duchess site) than for other crops. It should be stressed, however, that neither absolute temperature values nor the slope (sensitivity) can be derived from Figure 1.

Apparent temperature ranges of the five irrigation plots are shown in Figure 2 for both day and night data. Night temperature values were lower and had a low or no sensitivity to available water deficiency than the daytime measurements. The absolute temperature ranges also differed between crops for similar available water (AW) amounts, even for adjacent crops at the Duchess and Cassils sites. Due to the coarseness of the daytime temperature "slices", no final conclusions concerning the magnitude of differences caused by crop cover and time of day can be drawn from the data. It is encouraging, however, that the daytime temperature decreased consistently with increasing AW content for all plots. It is also of interest to note that the irrigation plots apparent temperature levels were higher than those for large fields at comparable soil moisture conditions. This might be due to advection effects but the available data do not allow establishing the reason with certainty.

Only daytime temperature ranges of the farm fields were available for this interim report. In Figure 3, these values were plotted against corresponding available water contents for all fields. The data included irrigated and dryland crops, rangeland, and a fallow field. The apparent temperatures exhibited a general decrease with increasing water content, but a considerable scatter is

evident as well. Energy balance considerations (Cihlar, 1976) as well as previous studies indicate that surface cover - particularly the relative proportions of green crop cover and bare ground - affects the surface temperature measured by an infrared remote sensor. Previous remote sensing studies established that the ratio of radiation reflected in near infrared and red portions of the electromagnetic spectrum increases with increasing crop cover. Therefore, we attempted to quantify the amounts of plant cover by using DRG which is defined as the difference between CIR transparency densities of the infrared - sensitive and the red - sensitive emulsion layers. A plot of DRG vs. apparent temperature (Figure 4) showed a close direct linear relationship between the two variables. Furthermore, the points were grouped into two clusters which coincided with irrigated (negative DRG) and dryland (positive DRG) sites. When the dryland sites were identified in Figure 3, they were found to be the highest apparent temperature values encountered. In other words, the lack of ground cover caused apparent temperature increase due to the increased exposure of bare soil. If only irrigated sites are considered in Figure 3, the relationship between temperature and available water is more closely defined. The goodness of fit of the temperature-water content relationship for irrigated fields (Figure 3) depends on the positions of three "outlier" data points (at AW = -11, 17 and 91%) which must be determined from more precise temperature data.

Relationships between remote sensing and ground variable were quantified using correlation analysis. Mid-values of the temperature "slices" were used in lieu of apparent temperatures. The following variables were included for all farm fields (a total of 18 data points):

DR = Density of the near IR - sensitive layer, dimensionless;

DG = Density of the red - sensitive layer, dimensionless;

DRG = Difference between DR and DG, dimensionless;

$T_{ap}$ = Apparent temperature (day value), $^{o}C$;

AW = Available water in the root zone, %.

The resulting correlation matrix (Table 1) shows that the apparent temperature was closely related to the difference DRG between red and green emulsion densities, which is in turn affected by the amount of green cover above the soil surface. The correlation between available water and $T_{ap}$ was quite low (-0.41). Correlation coefficients between $T_{ap}$ (dependent variable) and several independent variables were high when DRG was used, and fairly low otherwise (Table 2, data set DS1). The accuracy of predicting available water from $T_{ap}$ did not improve significantly when DRG was also used, and increased partially

after DR was added to the independent variables (r = 0.47, Table 2). The low improvement of the correlation coefficient suggests that DRG was only weakly related to the available water, and therefore did not improve the AW prediction. Since a definite relationship between soil water available at a given time and surface cover cannot be expected, variable surface cover would appear to be an intrinsic limitation of plant moisture stress determination through thermal infrared remote sensing.

Due to various crop types and degrees of surface cover being present in the data set and since the $T_{ap}$ values used were only approximate, an attempt was made to remove some of the uncertainties by reducing the data set in two ways. First, three seemingly anomalous points (at AW = -11, 17 and 91%) were ommitted to form a data set DS2 with 15 points. Secondly, irrigated fields from data set DS2 were put into data set DS3 which therefore contained 9 points. On the CIR transparencies, irrigated fields appeared to have a higher plant cover, were shown in deeper red colours, and soil was visible relatively seldom compared to the dryland fields. Correlation coefficients for various relationships were calculated for DS2 and DS3 in the same manner as for DS1.

The DS2 results were similar to those for DS1. Some improvements occurred, but were not very large even after including DRG and DR values (Table 2). In contrast, considerable improvement of AW prediction was found for DS3 (Table 3). In this case, DRG and $T_{ap}$ together explained 70% of the total variability of the AW values encountered in the irrigated farm fields data (r = 0.84, Table 2).

The above results were derived from averages of several soil moisture samples per farm field and a relatively crude measure of the apparent temperature. Although additional data and a more thorough analysis will be required to arrive at definitive conclusions, findings to data are consistent with the following statement. In the presence of variable plant cover (primarily percent cover) and variable available water content, the remotely sensed apparent temperatures correlate closely with plant cover and poorly with soil water. To the extent that plant cover is not systematically related to available soil water, AW values may not be reliably predicted from the thermal infrared data. On the other hand, if plant cover is uniform and the soil surface is shown in a minor way, the thermal data indicate plant stress and consequently available water in the soil profile.

## 5. FUTURE WORK

To provide definitive analysis and interpretation of the above indicated trends, the following tasks will be carried out:

(i) Digitize daytime thermal infrared data for the 5 August 1978 flight

(ii) Extract apparent temperature values for individual sampled sites on both irrigation plots and farm fields.

(iii) Extract apparent temperatures for the nighttime data from level-sliced thermograms.

(iv) Calculate day-night temperature differentials for 5 August 1978.

(v) Analyze the relationships between field data, thermal data, and photographic density measurements.

(vi) Confirm the validity of the conclusions using data from 20 June 1978 over the same area.

## 6. REFERENCES

Cihlar, J. 1976. Soil moisture determination by thermal infrared remote sensing. Proceedings of the Workshop on Remote Sensing of Soil Moisture and Groundwater, 8-10 November 1976, Toronto, Ontario.

Millard, J.P., R.D. Jackson, R.G. Goettelman, R.J. Reginato, S.B. Idso, and R.L. LaPado. 1977. Airborne monitoring of crop canopy temperatures for irrigation scheduling and yield prediction. Proceedings of the 11th International Symposium on Remote Sensing of Environment, Ann Arbor, MI 1453-1461.

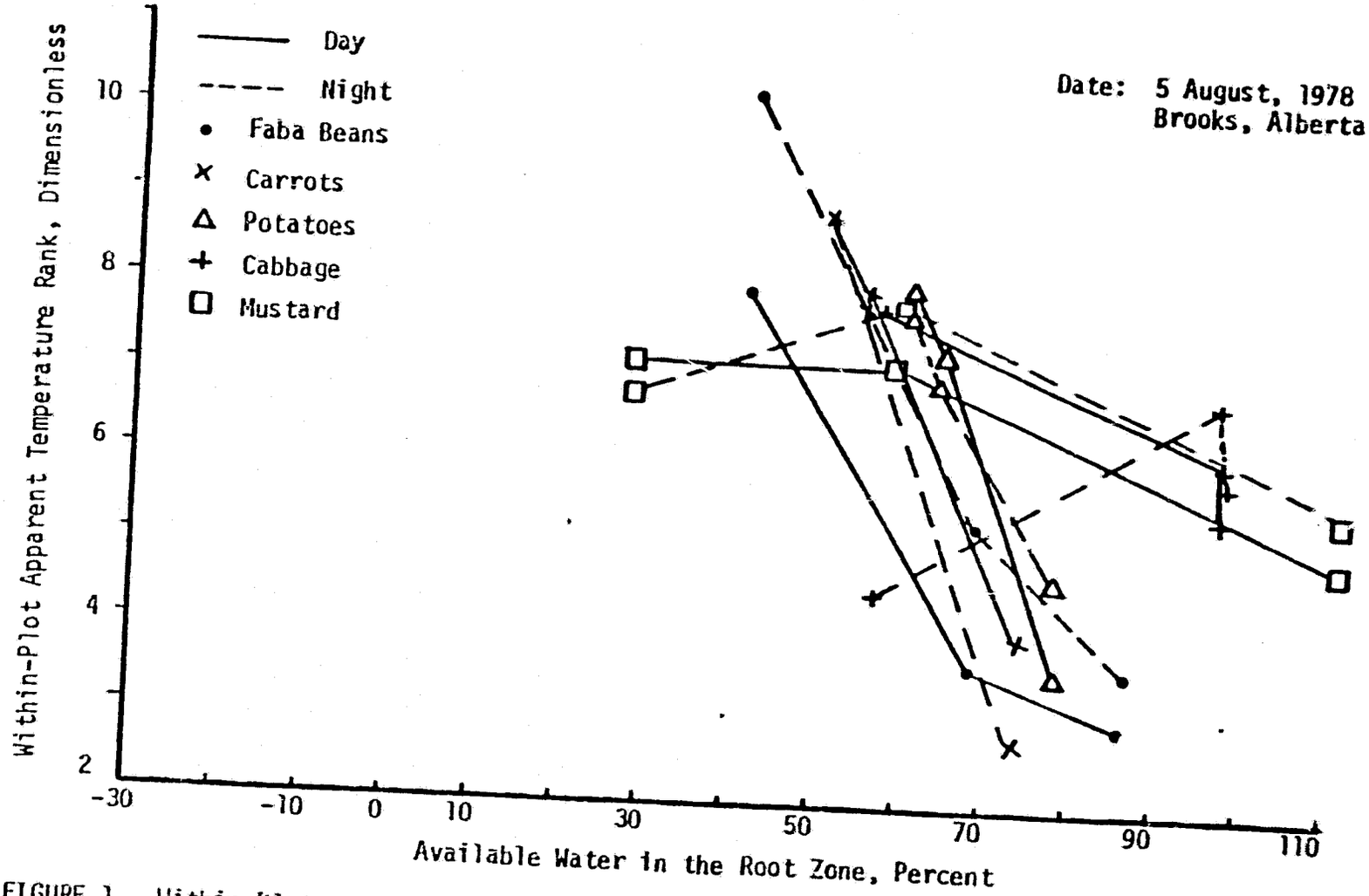



FIGURE 1. Within-Plot apparent temperature ranks plotted against the root zone water content. Ranks 1 through 12 were assigned to each treatment-replicate combination within a crop and time of flight.

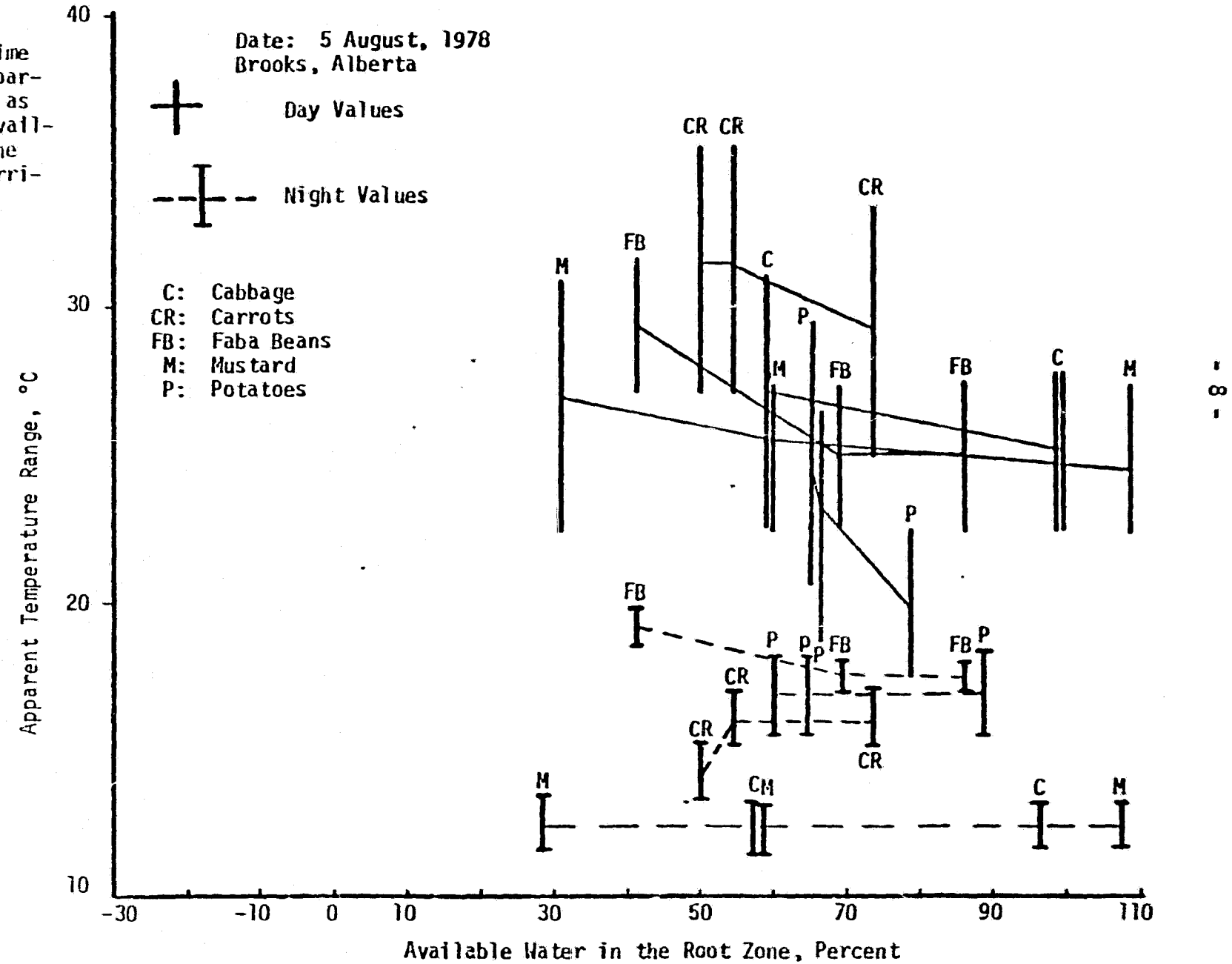



FIGURE 2. Daytime and nightime apparent temperature as a function of available water in the root zone for irrigation plots

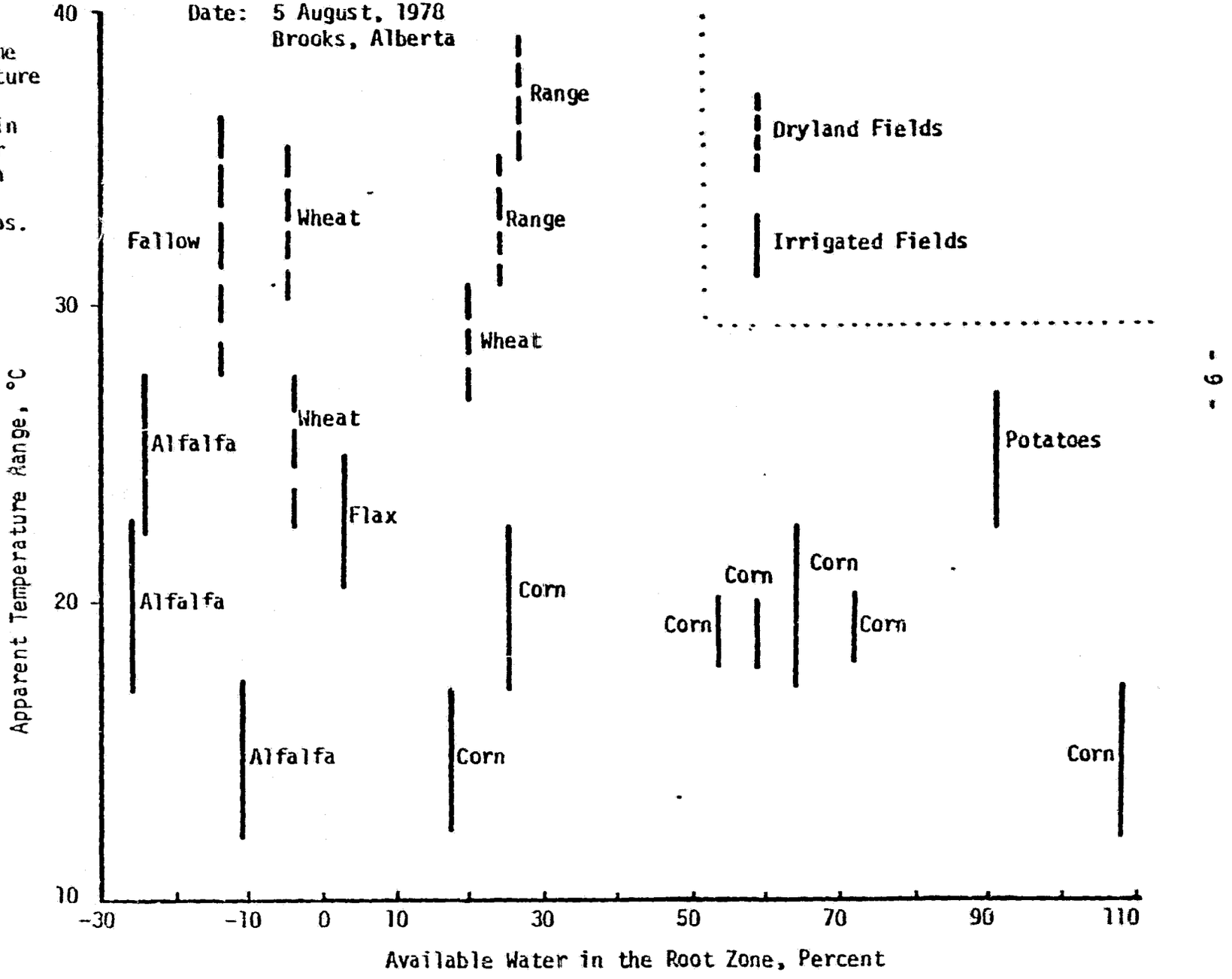



FIGURE 3. Daytime apparent temperature as a function of available water in the root zone for irrigated and non irrigated fields with various crops.

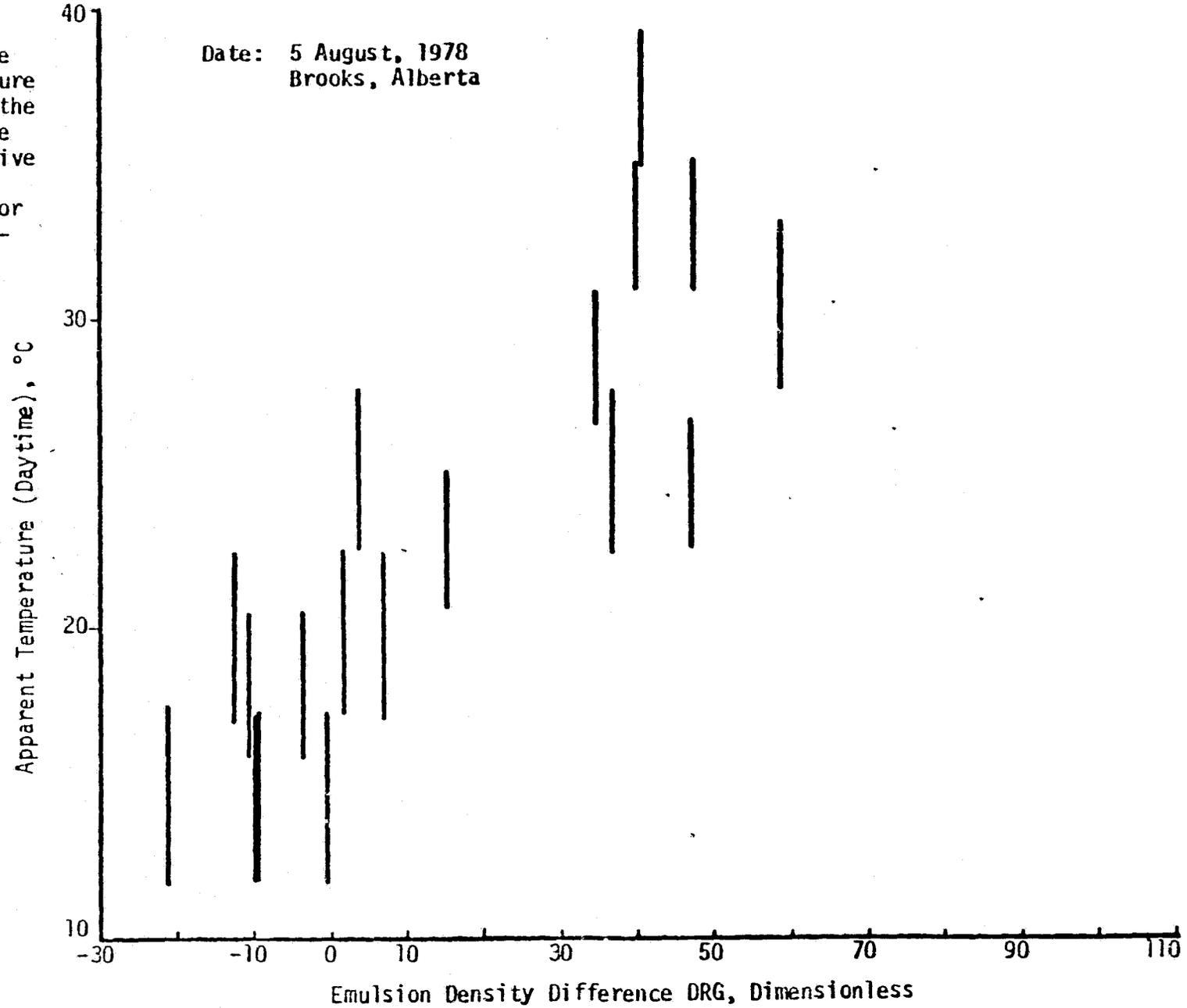



FIGURE 4. Daytime apparent temperature as a function of the density difference between IR-sensitive and red-sensitive layers of the color infrared transparencies.

Table 1. Correlation matrix for data set DS1 (all data, 18 points). **

| | | | | | |
|---|---|---|---|---|---|
| DR | 1.00 | | | | |
| DG | 0.31 | 1.00 | | | |
| DRG | 0.43 | -0.72 | 1.00 | | |
| $T_{ap}$ | -.27 | -0.70 | 0.86 | 1.00 | |
| AW | -0.33 | -.14 | -0:37 | -0.41 | 1.00 |
| | DR | DG | DRG | $T_{ap}$ | AW |

** 0.01 significance level: 0.58

Table 3. Correlation matrix for data set DS3 (irrigated fields only, DS3) **

| | | | | | |
|---|---|---|---|---|---|
| DR | 1.00 | | | | |
| DG | 0.81 | 1.00 | | | |
| DRG | 0.08 | -0.08 | 1.00 | | |
| $T_{ap}$ | 0.22 | -0.05 | 0.52 | 1.00 | |
| AW | -0.06 | -0.01 | -0.28 | -0.80 | 1.00 |
| | DR | DG | DRG | $T_{ap}$ | AW |

** 0.01 significance level: 0.62

Table 2. Correlation coefficients between available soil water and remote sensing variables for three data sets.

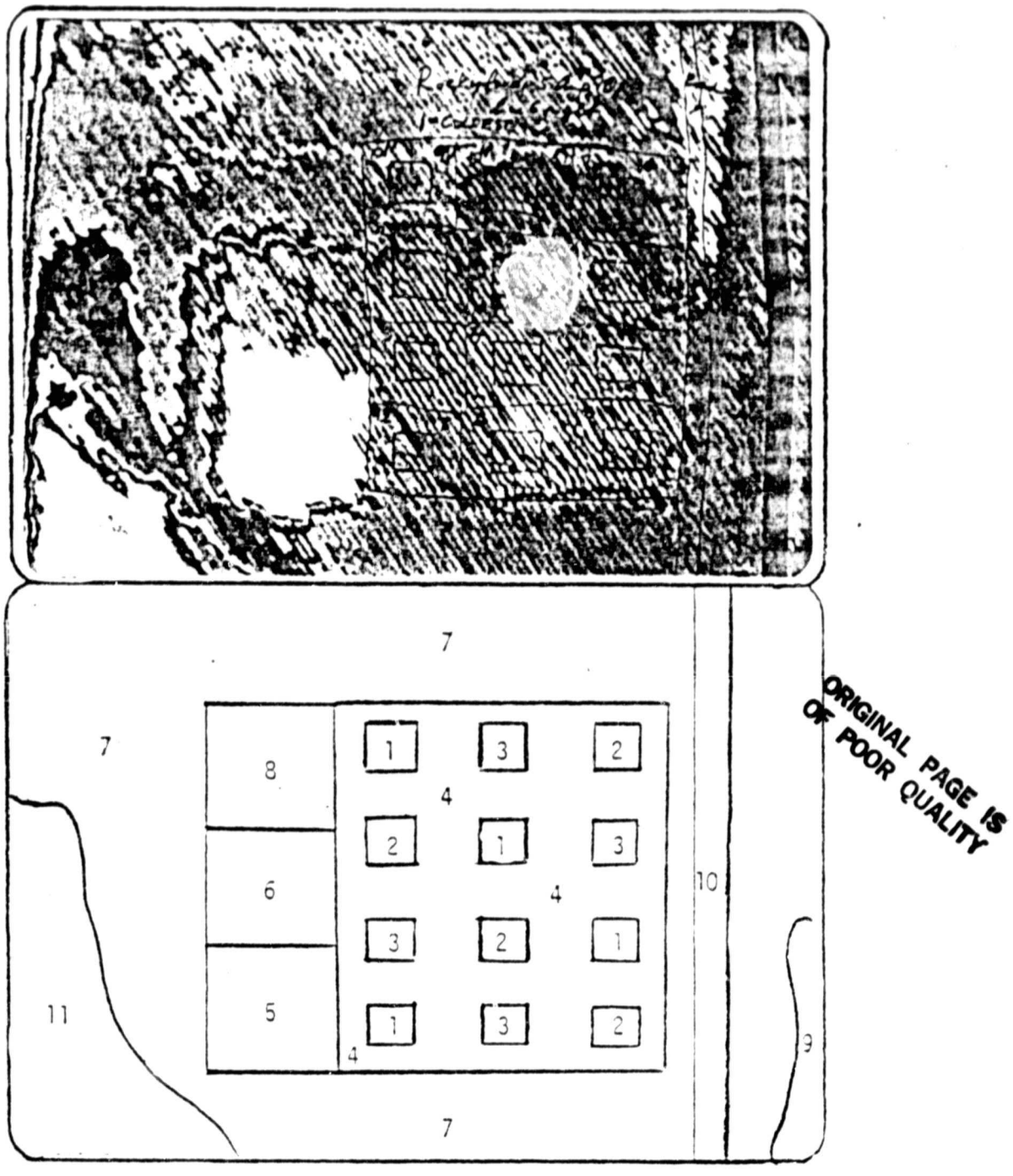
| VARIABLES | | CORRELATION COEFFICIENT FOR DATA SET + | | |
|---|---|---|---|---|
| DEPENDENT | INDEPENDENT | DS1 | DS2 | DS3 |
| $T_{ap}$ | AW | 0.41 | 0.54 | 0.80 |
| $T_{ap}$ | DRG | 0.86 | 0.82 | 0.40 |
| $T_{ap}$ | AW,DRG | 0.86 | 0.89 | 0.87 |
| $T_{ap}$ | AW,DRG,DR | 0.88 | 0.89 | 0.88 |
| AW | $T_{ap}$,DRG | 0.41 | 0.55 | 0.84 |
| AW | $T_{ap}$,DRG,DR | 0.47 | 0.57 | 0.85 |
| | | N = 18 | N = 15 | N = 9 |

+ Data set DS1: All data (18 points)

+ Data set DS2: Outlier points excluded (15 points)

+ Data set DS3: Only irrigated fields of data set 2 (9 points)

A Night Infrared Thermal Analogue Image (As Seen Under A Density Slicer) of A Faba Bean Irrigation Plot and Surrounding Area






1. Water 1 faba bean treatment under moisture stress. 2. Water 2 under slight moisture stress. 3. Water 3 under no moisture stress. 4. Border area of faba bean plots. 5. Plots of beans - soybeans, mung beans, faba beans, lentils which were recently irrigated to excess at the same rate as #6 which had a higher water use. 6. Plot of corn, forage sorghum, sorghum-sudangrass, and sorghum which was recently irrigated. 7. Wheat not irrigated severe stress. 8. Wild oats and weeds severe stress. 9. Summerfallow. 10. Roadway. 11. Grassland next to irrigation ditch moderate to no stress.

White, yellow, blue, green, red, mauve.
Coolest ⟶ hottest.

# SOIL WATER CONTENT ESTIMATION IN FALLOW FIELDS FROM AIRBORNE THERMAL SCANNER MEASUREMENTS

**by J. Cihlar**

*Applications Division,*
*Canada Centre for Remote Sensing, Ottawa*

**T. Sommerfeldt**

*Agriculture Canada, Research Station, Lethbridge*

**and B. Paterson**

*Alberta Agriculture, Irrigation Division, Lethbridge*

**SUMMARY**

*The purpose of this study was to determine if the relationship between diurnal surface temperature variations and near-surface soil water content may be used to determine soil water content from airborne measurements. Four flight missions with thermal infra-red and photographic sensors were conducted over an agricultural area in Southern Alberta during clear sky diurnal periods. Soil water content samples expressed in percent of field capacity (PFC), digitized thermal infra-red measurements, apparent temperatures at samples sites, and day minus night temperature differentials $\Delta T$, were obtained. Results confirmed the existence of an inverse linear $\Delta T$, vs PFC relationship under the experimental conditions, with near-surface water content generally the most important ground variable determining $\Delta T_r$. The $\Delta T$, vs PFC relationship was not improved by considering diurnal air temperature fluctuations, but did show various degrees of improvement when apparent radiances from the visible spectrum were included.*

## INTRODUCTION

Soil moisture is a very important parameter in studying, monitoring and modifying the behaviour of various land ecosystems (Idso et al, 1975a). The methods developed for its measurement can be divided into two groups (Cihlar and Ulaby, 1975): contact or direct methods which provide moisture estimates for a soil segment specifically examined or measured; and non-contact (or indirect) methods which do not require in situ measurements. The contact methods are costly when implemented over large areas, compared to non-contact methods (water balance and remote sensing approaches) which are less expensive and are therefore of primary interest for large-scale, operational soil moisture monitoring. The potential advantage of remote sensing approach is that every ground element is covered so that there is no need for interpolations or assumptions about the spatial variation of meterological and ground characteristics.

Three remote sensing techniques appear potentially suitable for satellite applications: thermal infra-red, active microwave, and passive microwave (Cihlar and Ulaby, 1975). The principles involved in the thermal infra-red method have been described by Idso et al (1975b), Idso and Ehrler (1976), Reginato et al (1976), Schmugge et al (1978) and Cihlar (1976). For bare soils, it was determined that the difference between maximum and minimum surface temperature during clear-day diurnal periods, $\Delta T_r$, was inversely related to the soil water content in the top 2 to 4 cm of the soil. The relationship varied with soil texture, but when soil water content was expressed in matrix tension, soil texture was not a factor (Idso et al, 1975b).

Since the surface temperature vs near-surface water content relationships established during controlled ground experiments were very promising (correlation coefficients exceeding 0.8 were obtained by Idso et al, 1975b), they were considered as a possible model for soil moisture monitoring from space. It was felt desirable to evaluate the effect of varying field and environmental conditions on the soil surface temperature — water content relationship. During 1976, the Canada Centre for Remote Sensing (CCRS), in co-operation with the Canada Department of Agriculture (CDA) and the Alberta Department of Agriculture, conducted an airborne experiment to determine how well the relationship holds over a larger agricultural area, what the effect of soil texture is on this relationship and how it can be removed, and if the estimation of soil moisture content could be improved by employing additional remote sensing data.

## MATERIALS AND METHODS

The study was carried out along an east-west line 32 km long south of Lethbridge, Alberta; approximate co-ordinates of the site centre are 49°27 'N, 112°42 'W. The site is in an agricultural area and includes irrigated and non-irrigated land. Four airborne missions were undertaken (Table 1) composed of one flight in the early afternoon and another after midnight, except for Mission 2 which was delayed (day flight) and aborted (night flight). During each flight, thermal infra-red line scanner data (Cihlar and Brown, 1977) were obtained with a 1.7 milliradian (Mission 1, 2, 3) or 2.5 milliradian (Mission 4) sensor. In addition, multi-band or colour film photographic data were also acquired during daytime flights (Table 1). Multi-band photographs were processed as negatives and the colour film as a positive.

Twenty-four fields were selected along the flight line. During Mission 1 and Mission 4, nearly all fields were fallow. For Missions 2 and 3, twelve fields were fallow, one planted with flax and the remaining eleven were planted with barley. In each field, sites were located near the road for repeated sampling during each mission. Figures 1(a), (b) and (c) show a typical fallow field during three missions. Samples were collected from two sites within each field (Figure 2) for gravimetric soil moisture determination. At each site, samples were taken at four depths (0-2, 2-4, 4-10 and 10-20 cm) from two locations five metres apart; the number of sub-samples varied with depth. Sampling usually commenced at 10:30 Local Solar Time (LST) and 22:30 LST and lasted four hours. During the afternoon sampling, vertical and oblique ground photographs were taken and plant weight, percentage of straw cover at the surface, and surface roughness were also determined. Apparent temperature measurements were made for eight fields with a PRT-5 radiation thermometer held vertically at one metre above the surface. Within several days of Missions 2 and 4, undisturbed soil samples were taken from the 0-5cm and 10-15cm depths of each field and used to determine bulk density values for individual layers through interpolation. Undisturbed cores, 15cm long, were extracted from six fields representing the various soils along the test site. In addition, disturbed samples were taken from each field and analyzed for particle size distribution and salt content.

Soil moisture characteristic curves in the tension range 0 to 500cm, a 15 bar water content and bulk density were obtained for each undisturbed core. Correlation matrix between sand, silt, clay, and 0.33 bar percentage showed that the best predictor for the 0.33 bar water content for the soils involved (assumed to equal field capacity) was the amount of sand (0.2mm — 2.0mm). The amount of clay reduced the remaining unexplained variability insignificantly. Therefore, the following regression equation was computed:

$$FC = 0.4022 - 0.00254S, \quad (1)$$

$$r^2 = 0.725, n = 7, \text{s.e.} = 0.022 \text{ g/cm}^3$$

where S is the amount of sand in percent for each field.

An inspection of calculated soil water contents indicated that, contrary to both theory and experimental results obtained during clear sky diurnal periods (Jackson et al, 1976), nighttime water contents were sometimes lower than those in the afternoon for the same sites. This discrepancy was probably caused by inaccurate depth measurements of the top layers at night, as moisture content increased with depth in all cases. For this reason, night moisture measurements

were used on
moisture val
quently, the
0–4cm, 0-10c
converted to

Proporti
from in situ e
which were
were employ
Table 2 give
measured for
parent radian

$R_{ap}$ (ban

Similar site
dividual emul
densitometer
density varia
of each site
frames) and

For anal
verted to dig
digitized, ac
displayed on
sor and know
over each sit
for pixels wit
and nighttim
site $\Delta T$, was

**Table 1**

**Airborne Data Characteristics**

| Mission | Date (1976) | Time of Flight (EST) | Meteorological Data* Air Temperature (°C) Maximum | Minimum | Relative Humidity (%) Maximum | Minimum | Site Conditions Prior to and During Overflights Cloud Cover** (%) | Wind | Dew | Data*** Collected |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 7 May | 1340 | 21.2 | 4.5 | 82 | 29 | 5–10 | Breeze | — | Package 1&2 |
| 1 | 8 May | 0110 | 25.7 | 7.6 | 76 | 22 | 0–5 | None | — | Package 2 |
| 2 | 1 June | 1520 | 18.9 | 3.7 | 66 | 22 | 5–10 | Moderate Gusty | — | Package 1&2 |
| 3 | 5 July | 1420 | 26.6 | 10.9 | 80 | 27 | 20–25 | Low | — | Package 1&2 |
| 3 | 6 July | 0255 | 30.0 | 8.2 | 80 | 27 | 0–5 | None or Breeze | Light to Heavy | Package 2 |
| 4 | 14 Sept | 1340 | 25.4 | 5.7 | 77 | 20 | 0 | Breeze | — | Package 3&4 |
| 4 | | 0030 | | | | | 0 | Moderate | — | Package 4 |

*Based on Ottawa Airport Weather Station data

**Of the total sky, estimated — Breeze < Low < Moderate

***Package 1: Kodak 2424 Pan IR film, 6" lens, 4 filters (Wratten 47B, 57A, 25, 88A)
Package 2: Thermal IR scanner imagery, 8–14 micrometres, resolution 1.7 milliradians
Package 3: Aerochrome Infra red Film, 6" lens
Package 4: Thermal IR scanner imagery, 8–14 micrometres, resolution 2.5 milliradians

| Mission | No. |
|---|---|
| 1 | |
| 2 | |
| 3 | |
| 4 | |

*One flax field

**For each item,

Legend: PS –
PC –

PB — percent b
PH — plant he

were used only if they were higher than the corresponding afternoon values. To obtain site moisture values for each layer, the afternoon and night measurements were averages; subsequently, the two locations within the site were averaged. Cumulative water contents for 0-2cm, 0-4cm, 0-10cm and 0-20cm were calculated by weighted averaging. These water contents were converted to PFC values using Equation (1).

Proportions of bare ground (PB), straw cover (PS), and plant canopy (PC) were compiled from in situ estimates, vertical ground photos, and oblique ground photos; both visual estimates which were repeatable to within about 10% and photographic density slicing (where possible) were employed to obtain the photo estimates. Plant heights (PH) were measured in the field. Table 2 gives ranges of these variables for Missions 1 to 4. Photographic densities (D) were measured for each site at each photo of the four bands (Missions 1, 2, 3) and converted to apparent radiances $R_{ap}$ using Equation (2):

$$R_{ap}(\text{band}) = 10^{D}(\text{band}) \qquad (2)$$

Similar site density measurements were made on colour film for Mission 4, except that individual emulsion layers were measured using the neutral, blue, green and red filters of a spot densitometer. Since the film was a positive, -D was the exponent used in Equation (2). To reduce density variations due to both sun/surface cover geometry and vignetting, density measurements of each site were made on two to four photographs (possible because of overlap of adjacent frames) and the readings were averaged.

For analysis, airborne thermal scanner measurements recorded during the flights were converted to digital form (256 levels). Since the lower and upper scanner reference signals were also digitized, accurate apparent temperature values could be obtained. The digitized data were displayed on the CCRS MAD/MICA image processing system. Using software-controlled cursor and known distances from landmarks to sampled sites, a 5m x 10m rectangle was positioned over each site, and apparent temperature statistics (mean, standard deviation) were computed for pixels within the rectangle. The same procedure was repeated for all sites on both afternoon and nighttime imagery. The maximum-versus-minimum surface temperature difference for a site $\Delta T$, was then obtained by subtracting the two means.

**Table 2**

**Ranges of Ground Variables for Fallow Fields***

| Mission | No. of Data Points | Ranges of** PFC Values At Depths 0-2 | 0-4 | 0-10 | 0-20 | PS (%) | PB (%) | PH (cm) | PC (%) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 48 | 32.2 | 48.5 | 61.9 | 75.3 | 3.0 | 30.0 | 0.0 | 0.0 |
| | | 70.6 | 78.0 | 112.6 | 127.4 | 70.0 | 92.0 | 9.0 | 10.0 |
| 2 | 24 | 10.9 | 14.8 | 33.0 | 42.7 | 15.0 | 40.0 | 0.0 | 0.0 |
| | | 54.6 | 56.2 | 64.5 | 84.9 | 60.0 | 85.0 | 15.0 | 15.0 |
| 3 | 24 | 10.6 | 26.9 | 55.2 | 69.7 | 10.0 | 25.0 | 0.0 | 0.0 |
| | | 29.5 | 45.9 | 75.4 | 94.8 | 63.0 | 90.0 | 17.0 | 23.0 |
| 4 | 48 | 13.1 | 22.2 | 47.1 | 59.4 | 0.0 | 0.0 | 0.0 | 0.0 |
| | | 67.9 | 74.6 | 110.6 | 122.3 | 82.0 | 100.0 | 56.0 | 100.0 |

*One flax field included for Missions 1 and 4.

**For each item, the maximum value is placed below the minimum value.

Legend: PS — percent straw
PC — percent plant cover
PB — percent bare surface
PH — plant height

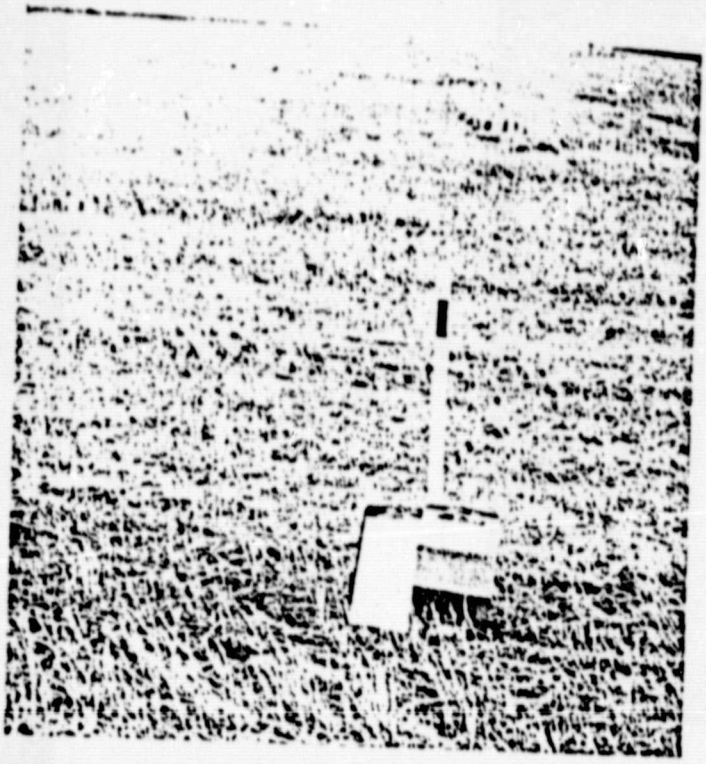


Figure 1 (a)
Typical fallow field during Mission 1, May 1976

FIE



Figure 1 (b)
Typical fallow field during Mission 3, July 1976

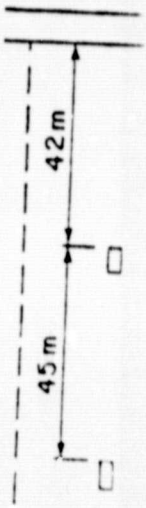



Figure 1 (c)
Typical fallow field during Mission 4, September 1976

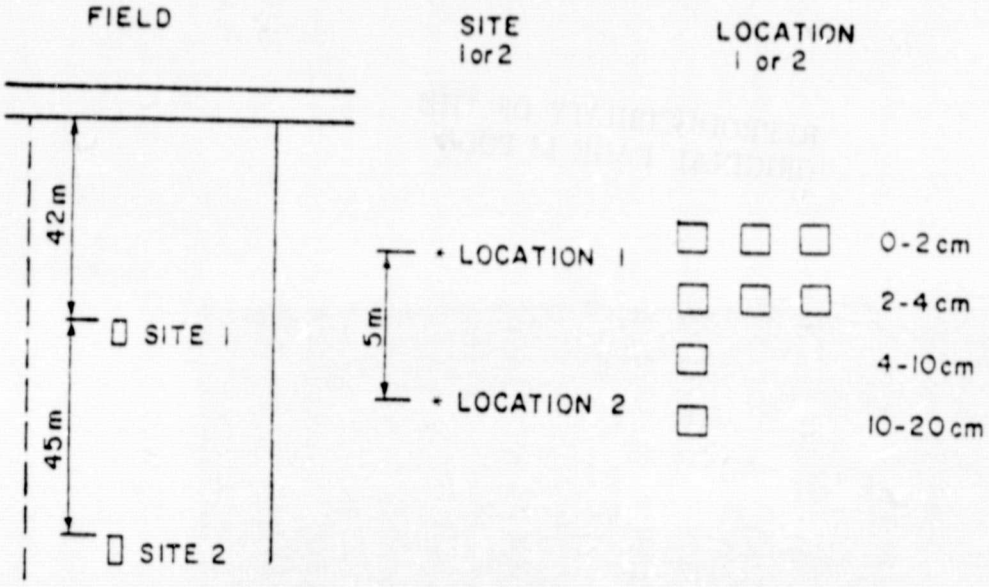



Figure 2
Sampling scheme for soil water content determination

## RESULTS AND DISCUSSION

Data from each mission were analyzed separately because of the time delay of Mission 2 (Table 1) which apparently obliterated the temperature response to soil moisture, and problems with absolute calibration of one reference plate which occurred during Mission 1.

### Effect of Soil Water Content

Figure 3 shows the relationship between the day minus night surface temperature differential ($\Delta T_s$) and soil water content in the top 2cm expressed in percent of field capacity (PFC) for Mission 1. Although the inverse linear relationship was clearly defined, appreciable scatter of data points occurred along the $\Delta T_s$ axis. While the scatter was enhanced by points in the upper right and lower left positions representing only three fields, it would exist even if these fields were ignored. The differences between fields appeared real because site variability was relatively small; the within-site standard deviation of apparent temperature was typically less than 1°C. The scatter may be partly attributed to uncertainties in soil moisture determination, since the average within-site standard deviation of PFC values was 8% and the additional uncertainty introduced by Equation (1) was of similar magnitude.

The $\Delta T_s$ vs PFC (0-2cm) plot for Mission 3 is shown in Figure 4. All fallow fields were dry as evidenced by the narrow range of PFC values. However, the spread of temperature differentials was larger than for the other missions. Mission 4 data (Figure 5) exhibited a well defined inverse linear relationship between $\Delta T_s$ and PFC (0-2cm). The scatter in the $\Delta T_s$ direction was of similar magnitude as for Mission 1, i.e. the scatter was larger at lower PFC values (the two data points near $\Delta T_s$ = 15°C represent a flax field). Compared to Mission 3, Mission 4 values were lower by a constant offset (6°C) as both calculated linear regression lines had a slope of -0.13°C/1% PFC.

Correlation coefficients r between PFC and $\Delta T_s$ for individual missions are shown in Figure 6 and with the exception of Mission 3, r values were highest for the top layer (0-2cm) and decreased with depth. The low Mission 3 values was probably due to the narrow PFC range, as correlation coefficients for deeper layers were similar to those from other missions. Secondly, r values for the 0-4cm layer were consistent throughout the season and almost as high as for the 0-2cm layer. Correlation coefficients for both layers improved when Mission 3 and Mission 4 data were combined, possibly due to a wider range of PFC values and a higher slope of the combined data set. Correlation between $\Delta T_s$ and PFC of deeper layers was generally low and inconsistent, thus suggesting a poor response of surface temperatures to water contents in deeper layers.

### Effect of Surface Cover on $\Delta T_s$

Figure 7 shows absolute values of correlation coefficients between $\Delta T_s$ and ground variables measured for fallow fields. Single and multiple correlation coefficients are given for individual and combined (3 + 4) missions and two layers, 0-2cm and 0-4cm. With the exception of Mission 4, near-surface soil water content was the most important variable. Mission 4 was flown shortly after harvest, and large portions of fields were covered with a mulch of fresh straw (40% of all fields had straw cover of 60% or higher); this factor was probably responsible for the high correlation. Compared to Figure 7, correlation coefficients for PB, PH, PC and PS would change to 0.81, -0.19, -0.32 and -0.80 respectively if the flax field data were omitted from Mission 4. For Missions 1 and 3, the straw mulch did not have a significant effect on measured $\Delta T_s$ values.

Multiple linear regression calculations indicate (Figure 7) that the surface parameters tested accounted for approximately 30% to 85% of total $\Delta T_s$ variability depending upon data set; Mission 3 surface layer was the lowest with only 8% of $\Delta T_s$ explained.

Only marginal improvements of multiple correlation coefficients were obtained after including surface cover descriptors (Figure 7). Mission 4 was the exception to this trend, as the proportion of bare ground (closely related to PS) increased the correlation coefficient substantially.

The effect of surface roughness was detected only with the PRT-5. A series of measurements made in September 1976 showed a definite inverse relationship between the

surface-air temperature differential and soil moisture (top 2cm). The lines for individual fields had an identical slope but were displaced vertically over a 4°C range. A comparison of surface roughness estimates for individual measurements indicated that smooth surfaces exhibited higher temperatures for equivalent water contents than rough surfaces. It appears that this effect was related to the sunlight/shadow ratio as determined by the solar zenith angle. The effect was not evident in the airborne data, probably because all fallow fields appeared equally rough for the selected cursor size.

The consistently high $\Delta T$, sensitivity to near-surface soil water content is encouraging, particularly since it persisted under natural conditions encompassing various soil, surface, roughness, straw cover and to some extent green vegetation conditions. Reasons for the low multiple correlation coefficients are not clear. Atmospheric or sensor effects may be excluded because the flight line was relatively short and the analysis was carried out for each mission separately. One reason might be inaccurate ground cover data. It should be noted, however, that apparent temperatures did not change substantially outside of the 5m x 10m rectangles delineated at each site as determined by enlarging the rectangle to 5m x 30m. Although the standard deviation increased somewhat, the mean value seldom varied by more than 1°C. This suggests that the surface conditions over a larger area were similar to those at the sampled sites, and thus the single set of ground cover estimates per field should be adequate. Another possible reason for the low multiple correlation coefficients shown in Figure 7 is the uncertainty of soil moisture estimates discussed previously. If this explanation is valid, it will imply better $\Delta T_s$ vs PFC correlation than indicated in Figures 3, 4 and 5.

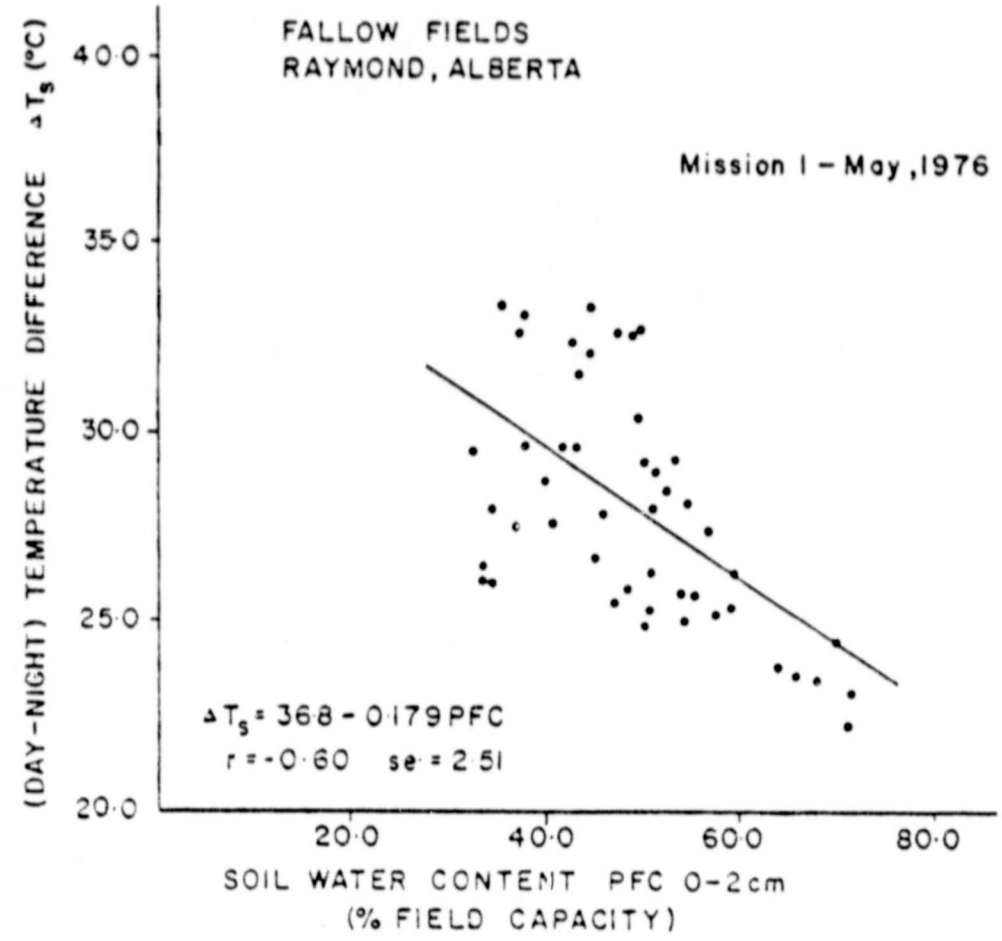



Figure 3
Diurnal soil surface temperature differential $\Delta T_s$ as a function of water content in top 2cm of fallow fields: Mission 1, May 1976

### Effect of Soil Texture on $\Delta T_s$

Correlation coefficients between $\Delta T_s$ and two measures of soil water content, percent of field capacity and volumetric water content are given in Table 3. Soil texture was clay loam (8 fields), clay (8), loam (4), and sandy clay loam (4). A decrease of r values for all cases is evident. The "difference" column in Table 3 indicates that an additional 5 to 26% of the total variability in the $\Delta T_s$ vs soil water content relationship could be explained when PFC was used as the soil water parameter.

Table 3 suggests that about an additional 15% of the total variability could be accounted for with PFC as the soil water content parameter. Considering that this fraction would increase further for a wider range of soil textures, it appears that the use of a tension-related measure of soil water for the thermal emission method is unavoidable. This is not necessarily a disadvantage since tension is a better indicator of soil water behaviour than water content; however, the use of a $\Delta T_s$ vs tension relationship would require the development of accurate predictive models.

### Stability of the $\Delta T_s$ vs PFC Relationship

A single, time-invariant soil water vs $\Delta T_s$ relationship would ideally be required for determining soil moisture remotely from thermal emission measurements. Since air temperature has a significant effect upon surface temperatures, temporal variations of air temperatures increase the uncertainty of soil water prediction. A procedure for removing air temperature effects from measured $\Delta T_s$ values was developed by Idso et al (1976) and used by Millard et al (1978).

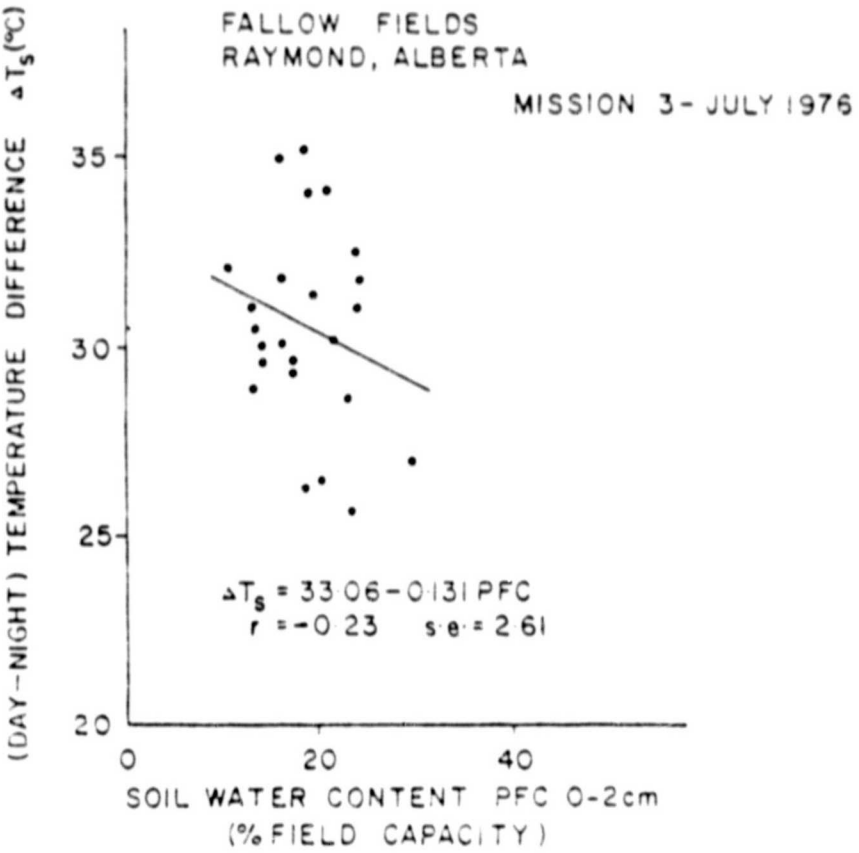



Figure 4
Diurnal soil surface temperature differential $\Delta T_s$ as a function of water content in top 2cm of fallow fields: Mission 3, July 1976

Table 3

Effect of Soil Texture On $\Delta T_s$ vs Soil Water Content Relationship

| Mission | Depth (cm) | Correlation ($\Delta T_s$, PFC) | Coefficient r ($\Delta T_s$, m.) | Difference in $r^2$ (%) |
|---|---|---|---|---|
| 1 | 0-2 | -0.60 | -0.45 | 16 |
| | 0-4 | -0.53 | -0.17 | 25 |
| 3 | 0-2 | -0.23 | -0.07 | 5 |
| | 0-4 | -0.57 | -0.26 | 26 |
| 4 | 0-2 | -0.68 | -0.62 | 8 |
| | 0-4 | -0.64 | -0.52 | 14 |
| 3 + 4 | 0-2 | -0.77 | -0.72 | 7 |
| | 0-4 | -0.72 | -0.62 | 13 |

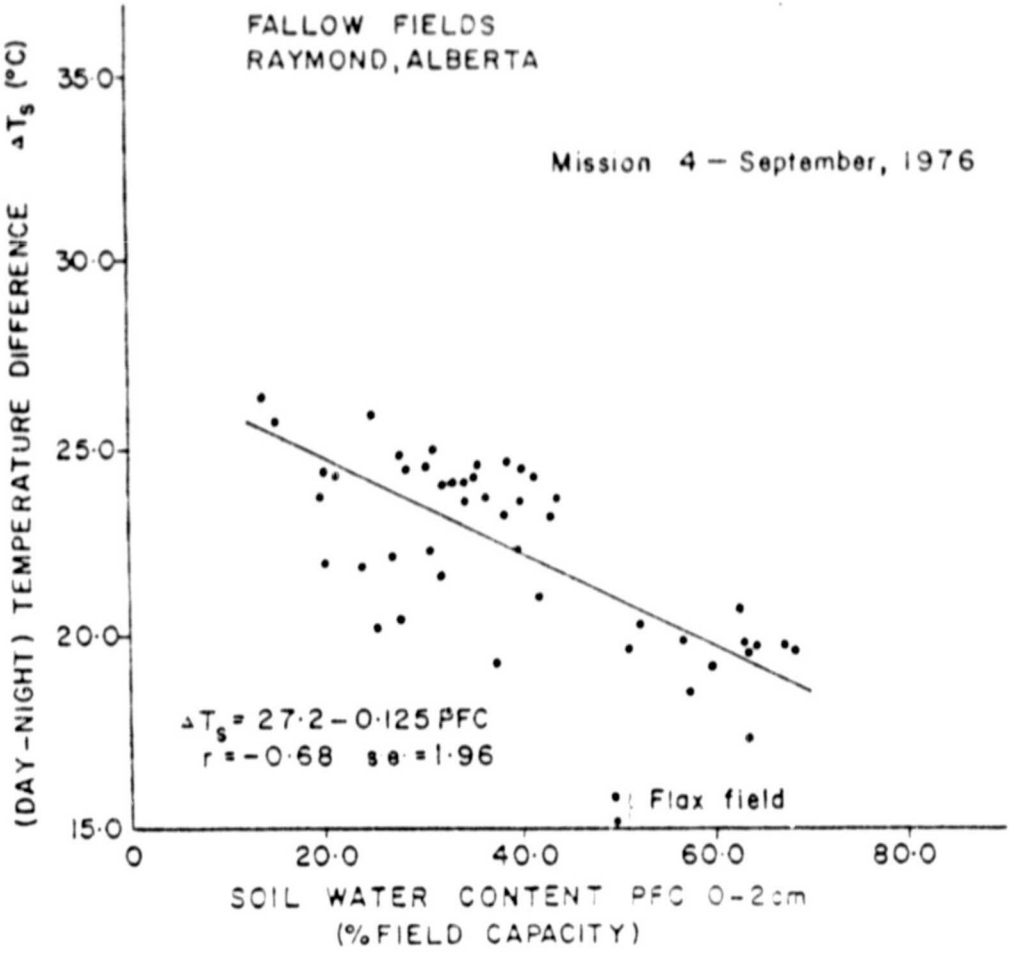



Figure 5
Diurnal soil surface temperature differential $\Delta T_s$ as a function of water content in top 2cm of fallow fields: Mission 4, September 1976

Table 4

**Diurnal Air Temperature Differentials $\Delta T_a$ and Regression Parameters for Three Missions**

| Mission | $\Delta T_a$ (°C) | Regression* Between $\Delta T_a$ and PFC (0–2cm) | |
|---|---|---|---|
| | | Intercept (°C) | Slope (°C/1% pFC) |
| 1 | 15.0 | 36.8 | -0.179 |
| 3 | 17.0 | 33.6 | -0.131 |
| 4 | 21.0 | 27.22 | -0.125 |

*Equation has the form:

$\Delta T_a$ = Intercept + (Slope) (PFC (0–2))

It involves calculation of normalized $\Delta T_m$ as follows:

$$\Delta T_m = \frac{\Delta T_a}{\Delta T_o} \Delta T_{mo}$$

where $\Delta T_a$ is the difference between maximum and minimum air temperatures for the diur period of interest, and $\Delta T_{mo}$ is the normalizing air temperature differential chosen as 18°C in references quoted above. When applied to data herein, the normalization should result in me ing the three regression lines into one.

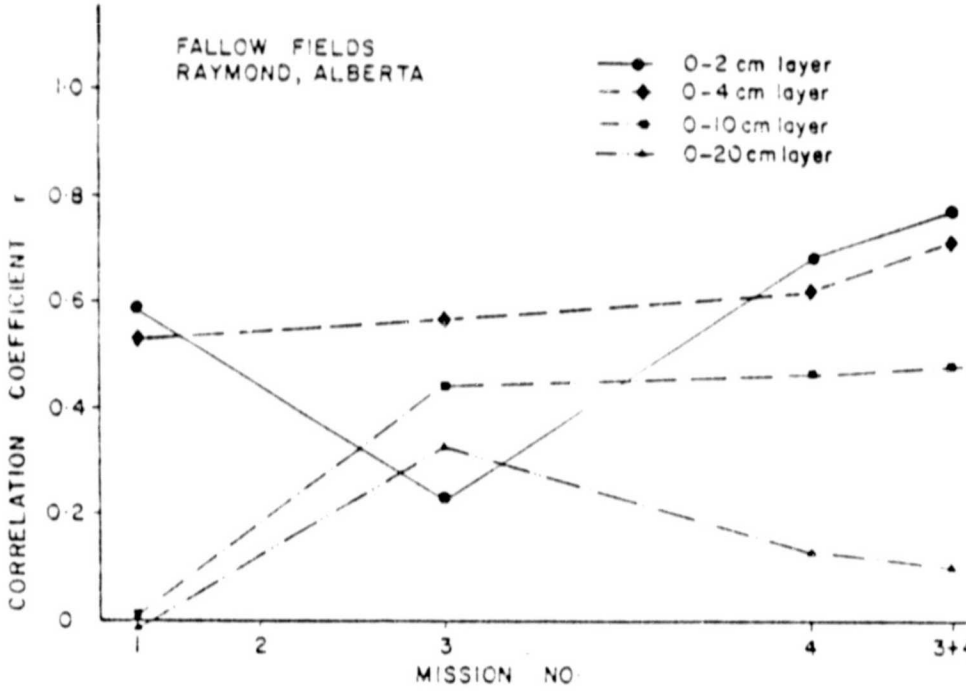



Figure 6
Correlation coefficient between the diurnal soil surface temperature differential $\Delta T_a$ and water conten four soil layers for various missions: fallow fields

Table 4 gives slopes and intercepts of the $\Delta T_s$ vs PFC (0-2cm) relationships and $\Delta T_a$ obtained as averages from surrounding meteorological stations for Missions 1, 3 and 4. Since Equation (3) should hold for all PFC values including 0%, the ratio of intercept to $\Delta T_a$ should be constant for the three missions. However, this ratio varied between 1.3 (Mission 4) and 2.5 (Mission 1) for data in Table 4. Consequently, use of this equation would increase rather than reduce the differences among individual missions

Assuming Equation (3) to be sound, discrepancies among individual data sets must be related to environmental conditions affecting the measurements or to the thermal scanners used. The high slope and intercept values for Mission 1 probably were due to faulty absolute calibration of the high temperature range which was detected during post-mission tests. Although within-mission comparisons remain valid, comparing results to other missions would not be warranted. On the other hand, scanners for Missions 3 and 4 were calibrated and the discrepancy between the data sets must be related to environmental conditions. Graphic and statistical analyses consistently showed that straw mulch cover was not responsible for the lower intercept of Mission 4. The atmosphere was somewhat hazy prior to the afternoon flight which could reduce the solar energy input and consequently lower surface temperatures somewhat. Also, the

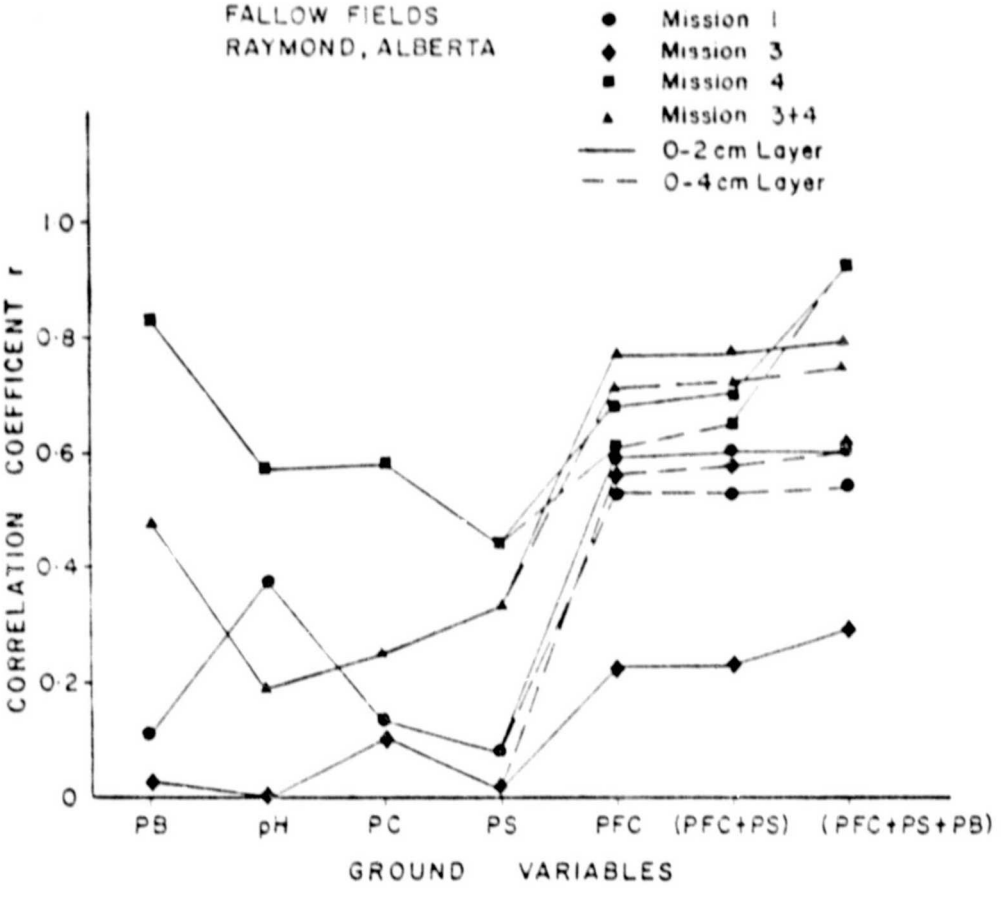



Figure 7
Single and multiple correlation coefficient values between the diurnal soil surface temperature differential $\Delta T_s$ and various ground variables: PB = percent bare ground, PH = plant height (cm), PC = percent plant cover, PS = percent straw cover, PFC = percent field capacity

wind was higher prior to and during Mission 4 (25km/h) than for Mission 3 (18km/h). Nevertheless, these factors do not appear to explain sufficiently the 7°C difference in intercepts. In fact, the Mission 4 intercept should be about 25% higher for the $\Delta T_s$ values given in Table 4 in order for Equation (3) to eliminate differences between the missions. Since diurnal air temperature extremes were consistent for all surrounding meteorological stations, they do not appear to be the cause of the discrepancy.

One reason for the observed lower intercept value for Mission 4 may be solar radiation. The solar noon zenith angle was 26.6° for Mission 3 and 45.7° for Mission 4. Since solar radiation incident on a horizontal surface is directly proportional to the cosine of the zenith angle, about 25% more radiation would be received during Mission 3. It is worth noting that the Mission 3 intercept was 21% higher than that for Mission 4. The zenith angle explanation does not account for increasing the discrepancy between intercepts by applying Equation (3), however.

### Effect of Reflected Solar Radiation

Figure 8 shows absolute values of single and multiple correlation coefficients between PFC (0-2cm) and remote sensing measurements. B1 through B4 represent apparent radiances for bands 1 through 4 (approximate wavelength ranges: B1 = 0.38 to 0.47 micrometres; B2 = 0.47 to 0.59 micrometres; B3 = 0.59 to 0.71 micrometres; B4 = 0.71 to 0.95 micrometres) determined as described under Materials and Methods. Correlation between PFC (0-2cm) and apparent spectral radiances was statistically significant for Missions 3 and 4 ($P < 0.01$), but was not consistent as evident from Mission 1 data. Since the surface soil of practically all fields was dry during the missions, the correlations for Missions 3 and 4 should be due to the relationship between surface cover and near-surface soil moisture. This was confirmed by multiple correlation analysis between PFC (0-2cm) and surface cover parameters which resulted in r values around 0.6 for Missions 3 and 4.

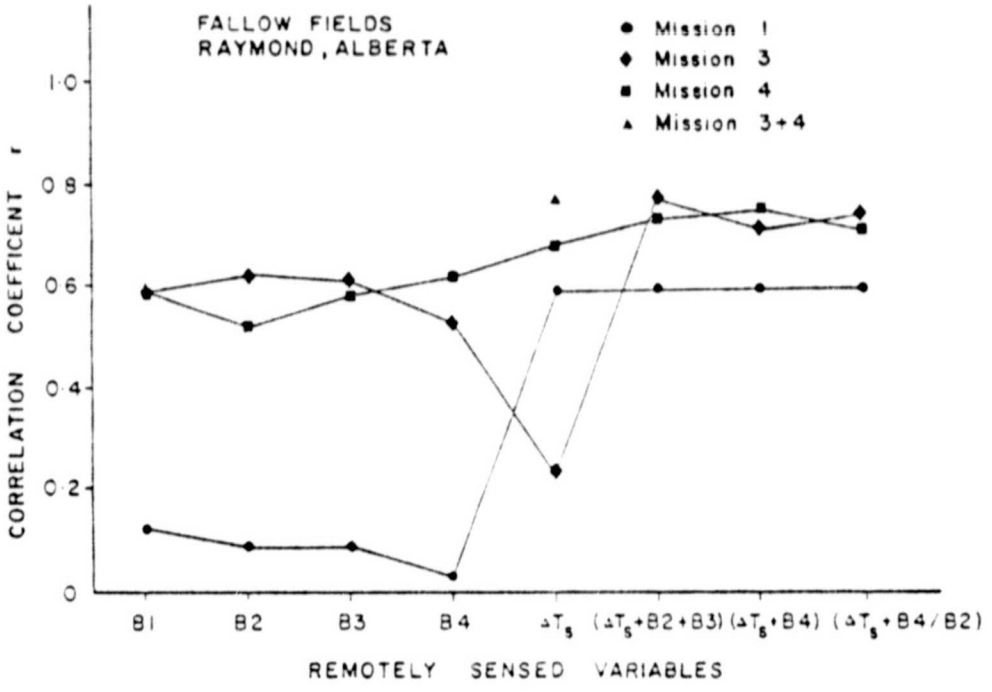



Figure 8

Single and multiple correlation coefficients between soil water content in top 2cm and several remotely sensed variables: B1 to B4 = apparent reflectance in four bands (0.38 to 0.47 micrometres, 0.47 to 0.59 micrometres, 0.59 to 0.71 micrometres, 0.71 to 0.95 micrometres); $\Delta T_s$ = diurnal soil surface temperature differential

Results shown in Figure 8 indicate that the addition of radiance data improved the accuracy of soil moisture estimation. The degree of improvement varied from high (Mission 3) to negligible (Mission 1). Due to film differences between Missions 3 and 4, their apparent radiances could not be combined. Since the soil water content range for Mission 3 was rather narrow, Missions 1 and 4 are probably more characteristic of the improvements in predictive accuracy that may result from including visible bands data. It is encouraging that the r values for the combination involving the band ratio were almost as high as for the actual values because ratios do not require data with absolute calibration. Considering the relatively crude measurement technique used to obtain the apparent radiance data, the results shown in Figure 8 should be treated with care. Evidently, some improvement of the predictive accuracy is possible, and a detailed study of this problem should be undertaken.

## SUMMARY AND CONCLUSIONS

A study of the relationship between diurnal surface temperature variations and near-surface soil water content yielded the following results:

1) Under clear sky condition, an inverse linear relationship existed between the day minus night surface temperature differential ($\triangle T_s$) and soil water content expressed in percent of field capacity (PFC) in the top 2 to 4cm of soil.

2) With the exception of the post-harvest Mission 4, near-surface water content was the most important ground variable, even under considerable straw mulch cover.

3) The variability of $\triangle T_s$ vs soil water relationship was reduced appreciably when soil texture was taken into account.

4) The temporal stability of the PFC vs $\triangle T_s$ relationship did not improve when diurnal air temperature variations were taken into account.

5) The relationship between PFC and $\triangle T_s$ improved to various degrees when apparent radiances from the visible spectrum were also included; correlation coefficients approached 0.8 (0.7) for the top 2cm (4cm) of the soil, respectively.

Results of this study indicate that the diurnal surface temperature variations correspond fairly closely to near-surface water content in fallow fields with various straw mulch, roughness, soil texture and seasonal conditions. Effects of other variables (surface slope, variable cloud cover) have not yet been examined. Future studies should include such variables, attempt to maximize the accuracy of soil water content prediction by using additional remote measurements, and development of a time-invariant, generally applicable predictive algorithm. If these problems are successfully solved, the thermal emission technique should become a useful tool for routine soil moisture surveys of fallow fields.

## REFERENCES


**Cihlar, J. and Ulaby, F.T. 1975** — *Microwave Remote Sensing of Soil Water in Agricultural Fields*, **Technical Report 264-5, Remote Sensing Laboratory, The University of Kansas Center for Research Inc., Lawrence, Kansas.**

**Cihlar, J. 1976** — *Soil Moisture Determination by Thermal Infra-red Remote Sensing*, **Proceedings of the Workshop on Remote Sensing of Soil Moisture and Ground Water, 8-10 November 1976, Toronto, Ontario, pp.206-215.**

**Cihlar, J., and Brown, R.J. 1977** — *Aerial Heat Loss Detection from Buildings*, **Engineering Digest 23(10), pp.29-31.**

**Idso, S.B., Jackson, R.D. and Reginato, R.J. 1976** — *Compensating for Env Variability in the Thermal Inertia Approach to Remote Sensing of Soil Moisture,* **Jou plied Meteorology 15, pp.811-817.**

**Idso, S.B. and Ehrler, W.L. 1976** — *Estimating Soil Moisture in the Root Zone o Technique Adaptable to Remote Sensing,* **Geophysical Research Letters 3, pp.23-25.**

**Idso, S.B., Jackson, R.D. and Reginato, R.J. 1975(a)** — *Detection of Soil Moisture Surveillance,* **American Scientist 63, pp.549-556.**

**Idso, S.B., Schmugge, T.J., Jackson, R.D. and Reginato, R.J. 1975(b)** — *The Utility Temperature Measurements for the Remote Sensing of Soil Water Status,* **Jou Geophysical Research 80, pp.3044-3049.**

**Jackson, R.D., Reginato, R.J. and Idso, S.B. 1976** — *Timing of Ground Truth During Remote Assessment of Soil Water Content,* **Remote Sensing of Envi pp.247-255.**

**Millard, J.P., Jackson, R.D., Goettelman, R.C., Reginato, R.J. and Idso, S.B. 19** *Water-Stress Assessment Using an Airborne Thermal Scanner,* **Photogrammetric E and Remote Sensing 44, pp.77-85.**

**Reginato, R.J., Idso, S.B., Vedder, J.F., Jackson, R.D., Blanchard, M.B. and Goe 1976** — *Soil Water Content and Evaporation Determination by Thermal Paramete from Ground-based and Remote Measurements,* **Journal of the Geophysical R pp.1617-1620.**

**Schmugge, T., Blanchard, B., Anderson, A. and Wang, J. 1978** — *Soil Moisture S Aircraft Observations of the Diurnal Range of Surface Temperature,* **Water Resour 14, pp.169-172.**